LCA Case Studies

Influence of Derived Operation-Specific Tractor Emission Data on Results from an LCI on Wheat Production

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Abstract

The shortage of data for emissions from agricultural tractors contributes to LCA results on environmental load from modern crop production possibly having high error levels and high uncertainties.
The first part of this work describes measurements and calculations made in order to obtain operation-specific agricultural emission data. Calculations are based on emission data measured on a standard 70 kW tractor of a widely available make. In the second part, results from an LCI on wheat production based on traditionally used emission data are calculated and compared with results obtained when using the emission data for specific working operations derived in part one.
One conclusion of the study is that the emission values, when related to the energy in the used fuel, show very large variations between different driving operations. Another conclusion is that the use of the new data results in a marked reduction of the total air emissions produced in the wheat production chain, especially for CO and HC, but also for NO_x and SO_2.

Keywords: Agriculture; data quality; emissions; food production; LCA; Life Cycle Assessment; vehicles

1 Introduction

Environmentally friendly and sustainable production of food is of major importance for the future welfare of the growing human population. Modern food production, however, is based on the use of large diesel-fuelled vehicles. Emissions from these vehicles contribute to the environmental impact caused by anthropogenic emissions. Results from LCA analyses performed on agricultural products have shown that emissions from internal combustion engines might make an important contribution to the environmental load (Cederberg, 1998; Välimaa and Stadig, 1998).

Agriculture is both a source and a sink for emissions. Skärby et al. (1995), for instance, showed that increased photochemical ozone creation causes a yield reduction of 5% in Swedish agriculture as compared with yields that would have been possible with pre-industrial ozone levels.

Very little data is available on the discharge of emissions from agricultural tractors (Hansson et al., 1998). Therefore, the data used in most LCA studies are from measurements on diesel-fuelled trucks or from large wheel loaders. Audsley et al. (1997) present data aimed for use in LCA studies including agricultural operations. The emission factors presented originate from Fenhann and Kilde (1994), and were taken from COPERT which is a computer programme to calculate emissions from road traffic. Tillman et al. (1991) present emission data that is frequently used in Swedish LCA studies including agriculture. This data is also from road traffic vehicles. There are many reasons to believe that road traffic emission figures are not representative for tractors performing typical agricultural working operations (Treiber and Sauerteig, 1991; Hansson et al., 1998).
Recorded time series of engine speed and loading torque on a tractor engine show that variations in the typical load strongly depend on the working operation performed (Norén and Browén, 1988). Available data also show that the amount of emissions from a diesel motor measured in relation to the energy in the combusted fuel is highly dependent on the engine speed and loading moment (Hedbom, 1994). In spite of that, tractor emissions in LCA analyses are calculated from the assumed fuel consumption using one single factor, independent of the type of operation performed.
Standardised measurements of emissions from engines used in agricultural tractors are performed according, for example, to the ISO 8178 C1 or ECE R49 standards. The emissions are then measured at 8 or 13 combinations of engine speeds and loading torque and the results weighted together to one single value. The weighting factors are standard and not designed especially for agricultural conditions. Therefore, the results cannot be assumed to be representative for agricultural tractors (Cornetti et al., 1988; Treiber and Sauerteig, 1991).
The shortage of data on emissions from tractors contributes to LCA results on the environmental load from modern crop production, possibly having high error levels and high uncertainties.
The first part of this work describes measurements and calculations made in order to obtain emission data for an ag-

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ricultural tractor, i.e. a standard 70 kW Valmet when used in typical agricultural operations. In the second part of the work, results from an LCI on wheat production based on traditionally used emission data are calculated and compared with results obtained when the new emission data, based on specific working operations, are used.

In order to obtain emission values specific for different driving operations, time series for the load on the tractor engine were recorded when performing typical operations. Bilinear interpolation, based on available ECE R49 test bench emission data, was then used to calculate the discharge of emissions at each point in the recorded time series. These results were finally integrated to obtain the total emissions for each of the recorded operations.

2 Emission Data

2.1 Engine load recording

The load on an agricultural tractor engine was recorded when performing several driving operations. The tractor used was a Valmet 805, a standard 70 kW tractor made in Finland with turbo and four-wheel drive. The tractor was supplied with standard tyres and in other respects was equipped and adjusted for normal Swedish conditions.

The data acquisition system is described by Browén (1988). The sample time was 7.5 s and the maximum measurement length was 2.8 h. The recorded signals were used to calculate output parameters such as engine speed, fuel consumption, output power, gear level, ground speed and slip.

The calibration of the measurement system is described by Norén and Browén (1988). The system was calibrated by braking in a test bench and via the simultaneous determination of fuel consumption, exhaust temperature and engine speed. The calibration results show that it was possible to calculate engine power output with high accuracy ($r = 0.9973$) using data for engine speed and fuel consumption.

About 40 recordings were made under varying circumstances and when performing different working operations. The tractor was operated by the same well-experienced driver in all measurements. After a preliminary analysis, the most representative recordings were chosen for a more thorough analysis. For this study, the following operations were considered to be interesting:

1. Stubble cultivation with a 3.5 m wide disc harrow adjusted for 0.05 m working depth
2. Ploughing with a 1.55 m wide mounted reversible plough adjusted for a working depth of 0.23 m
3. Harrowing with a 5.7 m wide seed-bed harrow adjusted for normal seed depth
4. Sowing with a 3.0 m wide towed seed drill adjusted for normal seed depth
5. Transport of 8.8 tonnes of sand on the highway and in town traffic using an 8-tonne single-axle trailer
6. Transport of grain from the field to the farm silo using a 12-tonne tandem-wheel trailer.

The working operations studied are described in Table 1.

2.2 Emission calculations

ECE R49 test data was used as an input to the emission calculations. ECE R49 states that the CO, NO_x and HC emissions are measured at 13 combinations (modes) of engine speed and loading torque. Three test modes (numbers 1, 7 and 13) are identical, and the results from the tests consequently describe the emissions at 11 different working points.

Data for each mode in an emission test are normally not published and no such data was available for the engine in the Valmet 805 tractor. However, emission data were available for a Valmet 420 DS engine. This engine is almost identical to the engine in the Valmet 805. Both are 4 cylinder turbo engines with a cylinder volume of 4.4 l, and a maximum power of 70 kW. The 420 DS engine is mounted in the Valmet 6400 tractor which came onto the market in 1991 and is still in production. It is assumed that the resulting load at the engine in the Valmet 6400 is identical to the load at the engine in the Valmet 805 when performing the same driving operation, which seems very reasonable since the Valmet 6400 is just a modernised version of the Valmet 805. The emission values presented in this work are therefore representative of operations performed with the Valmet 6400 tractor.

The emission data are measured by SMP (the former Swedish National Machinery Testing Institute). A summary of the results are included in SMP (1993). The engine was equipped to a standard level and factory-adjusted for driving on diesel fuel. When performing the measurements, the fuel was standard diesel ("winter" diesel in Sweden) with 0.2 % content of sulphur, an energy content of 42.8 MJ/kg and a density of 0.826 kg/l.

By using the emission values at the 11 combinations of engine speed and loading torque defined in the standard as input data, it was possible to calculate emissions for every possible combination of engine speed and torque measured at the engine, by using bilinear interpolation. Calculations were performed for all data points in the time series recorded. The methodology is described in greater detail in Hansson et al.

Table 1: Description of the analysed measurements

Operation	Time (min)	Distance (km)	Average velocity (km/h)	Average slip (%)	Average speed (rpm)	Average power (kW)
Stubble cult.	166.0	9.25	6.96	8.09	1983	31
Ploughing	158.1	9.83	3.43	16.33	1587	27
Harrowing	105.1	10.31	5.88	23.07	2057	61
Sowing	168.3	20.55	7.33	6.77	1560	20
Transport 1	151.5	68.3	27.05	3.15	2167	26
Transport 2	104.2	21.2	12.20	7.30	1498	17

(1998). The calculated emissions are shown in relation to the energy in the fuel used (→ *Table 2*).

Table 2: Discharge of emissions in relation to the energy in the used fuel when performing different working operations

Operation	CO (g/MJ)	NO_x (g/MJ)	HC (g/MJ)
Stubble cult.	0.076	0.747	0.030
Ploughing	0.085	0.988	0.029
Harrowing	0.042	0.897	0.016
Sowing	0.108	0.948	0.034
Transport 1	0.100	0.708	0.032
Transport 2	0.150	0.900	0.037

Table 3: Calculated discharge of emissions and fuel consumption when performing different working operations

Operation	CO (g/ha)	NO_x (g/ha)	HC (g/ha)	Fuel cons. (l/ha)
Stubble cult.	14.65	143	5.68	5.41
Ploughing	49.3	573	17.07	16.4
Harrowing	9.27	198	3.49	6.25
Sowing	13.21	117	4.20	3.47
	(g/km)	(g/km)	(g/km)	
Transport 1	1.28	9.09	0.414	
Transport 2	2.83	16.84	0.687	

The emission values are also calculated in relation to the cultivated area and, for the transport operations, in relation to the driving distance (→ *Table 3*). The driving distance was recorded with a small 5th wheel on the tractor. To compensate for overlap, the effective widths for the harrow and the disc cultivator are reduced by 10 %. To compensate for driving with the implement not in work, for example at headlands and around obstacles, the effective distance for all implements is reduced by 10 %. No compensation is made for the transport operations.

3 Influence of Tractor Emission Data on An LCI of Wheat

3.1 Description of the system

The different emission data sets were applied to an LCI case study with the aim of investigating the importance of the choice of emission factors on some fossil fuel related air emissions. The functional unit in the calculations is 1 kg of winter wheat with 15% moisture content. The inventory data as regards plant nutrients and crop yield originate from a study reported by Välimaa & Stadig (1998). The crop was grown in the south-western part of Sweden with a crop yield of 6970 kg/ha. Amounts of 60 kg/ha phosphorus and 164 kg/ha nitrogen were applied, and fertiliser production was included in the calculations. The field emissions related to fertiliser supply were 0.95 g nitrate-N to water, 0.22 g ammonia to air 0.37 g N_2O and 0.089 g phosphorus per kg grain with 15 % w.c. (Välimaa and Stadig, 1998).

Only one pesticide treatment was carried out: a mixture of the two herbicides tribenuron methyl (4.5 g/ha) and fluroxipyr (90 g/ha) was applied. Data on fertiliser production originates from Weidema et al. (1995) and data on pesticide production from Green (1987) and Audsley et al. (1997).

The system studied is schematically described in **Figure 1**. The production and end use of diesel fuel and artificial fertilisers are included in the calculations but not the manufacturing and maintenance of agricultural machines. The wheat straw was incorporated into the soil and no environmental burden was therefore allocated to it.

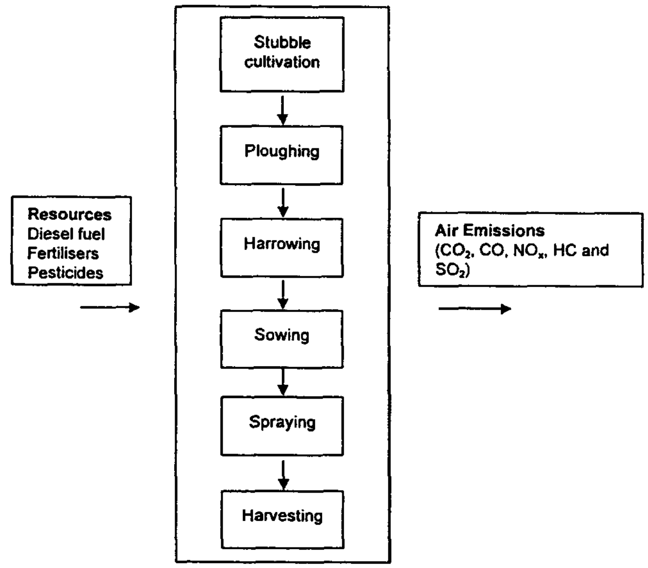

Fig. 1: Principal flow chart of the wheat cultivation system studied

The diesel fuel consumption for each operation is described in **Table 4**. Note that harrowing and fertilising were done twice in the production cycle. Since no data for fertilising or spraying operations were available from the previously described study, capacity data for these two operations are taken from SLU (1989). The characteristics of the load at the tractor engine at fertilising and spraying were assumed to be equivalent to the load at sowing. The distance between the field and the farm was assumed to be 1 km. The harvester's fuel consumption is a typical value reported from a Swedish farm (pers. comm. Hovelius, 1998).

Calculations of the environmental load were performed using three different types of emission data keeping all the other parameters constant. The emission data used is summarised in **Table 5**. The calculation for **Case 1** is based on emission data used in earlier studies of agricultural production (Cederberg, 1998; Mattsson, 1999). This data applies to all types of diesel use and is not specific for agricultural tractors. It is also included in LCAiT, which is a publically available and widely used Swedish software for LCA calculations (LCA inventory tool, 1995).

Case 2 is based on results reported earlier in this work, with emission data measured on a typical agricultural tractor engine. However, no consideration is paid to variations between different operations. The same emission factor, calculated with the general weighting factors defined in ECE R49, is used for all tractor operations. **Case 3** is also based on emission data from the agricultural tractor engine, but in this case with consideration taken to variations in the load characteristics between different types of operations.

Table 4: Fuel consumption for different working operations

Operation	Fuel cons. (l/ha)	Fuel cons. (MJ/ha)	Fuel cons. (MJ/kg wheat)
Stubble cultivation	5.41	191	0.0274
Ploughing	16.4	580	0.0832
Harrowing [a]	12.5	442	0.0634
Sowing	3.47	123	0.0176
Fertilising [a]	4.40	156	0.0224
Spraying	1.36	48.1	0.0069
Harvesting	15.0	530	0.0760
Transport to farm	0.71	530	0.0036

[a] Harrowing and fertilising were carried out twice

Table 5: Emission factors used in the three cases (in g/MJ diesel)

Operation	Case 1 CO (g/MJ)	Case 1 NO_x (g/MJ)	Case 1 HC (g/MJ)	Case 2 CO (g/MJ)	Case 2 NO_x (g/MJ)	Case 2 HC (g/MJ)	Case 3 CO (g/MJ)	Case 3 NO_x (g/MJ)	Case 3 HC (g/MJ)
St. cult.	0.300	1.300	0.200	0.095	1.057	0.025	0.076	0.747	0.030
Ploughing	0.300	1.300	0.200	0.095	1.057	0.025	0.085	0.988	0.029
Harrowing	0.300	1.300	0.200	0.095	1.057	0.025	0.042	0.897	0.016
Sowing	0.300	1.300	0.200	0.095	1.057	0.025	0.108	0.948	0.034
Fertil.	0.300	1.300	0.200	0.095	1.057	0.025	0.108	0.948	0.034
Spraying	0.300	1.300	0.200	0.095	1.057	0.025	0.108	0.948	0.034
Harvesting	0.300	1.300	0.200	0.300	1.300	0.200	0.300	1.300	0.200
Transport	0.300	1.300	0.200	0.095	1.057	0.025	0.131	0.780	0.032

The third case is therefore based on the "best" data available. Since no new data was available for the emissions from the self-propelled harvester, the data based on Tillmann et al. (1991) was used for the harvest operation in all three calculations.

In Case 1, the SO_2 emission figures from the LCAiT database based on data reported by Tillmann et al. (1991) were used: 0.140 g/MJ. In Cases 2 and 3, the SO_2 emissions are decided from the sulphur content in the fuel and defined as 0.0935 g/MJ. The CO_2 emissions in all three cases are defined as 74.6 g/MJ (also based on Tillmann et al., 1991).

3.2 Impact of the choice of emission factors

The calculated emissions from the tractors in the field when producing 1 kg wheat are described in **Table 6**, together with the relations between the results from the different scenarios. **Table 7** shows the amount of emissions produced in the total production cycle.

4 Discussion and Conclusions

The emission values reported are calculated using data from one type of agricultural engine and tractor. The lack of detailed published data for other tractor engines makes it difficult to estimate if the engine studied is perfectly representative of the average modern tractor engine, and it is important to note that the results presented can not be used as average values for all modern tractors. However, unpublished data from measurements made on several Valmet engines indicate that the CO and NO_x values for the 420 DS engine are close to average, while the tested engine provides somewhat lower HC values than average.

The results of the emission measurements show very large variations between different operations when the emissions are described in relation to the energy in the fuel used. The differences, for example, between harrowing and transporting, are as high as 3-4 times for CO and HC emissions. Also the NO_x values differ, but these variations are not so

Table 6: Tractor emissions when producing 1 kg wheat calculated with three different types of emission input data

Emission	Case 1	Case 2	Case 3	Case 3/Case 1	Case 3/Case 2
CO_2	16.7	16.7	16.7	1	1
CO	0.0607	0.0202	0.0168	0.28	0.83
NO_x	0.265	0.217	0.195	0.74	0.90
HC	0.0422	0.00766	0.00796	0.19	1.04
SO_2	0.0318	0.0228	0.0228	0.72	1

Table 7: Total emissions when producing 1 kg wheat calculated with three different types of emission input data

Emission	Case 1 (g/kg wheat)	Case 2 (g/kg wheat)	Case 3 (g/kg wheat)	Case 3/Case 1	Case 3/Case 2
CO_2	98.5	98.5	98.5	1	1
CO	0.0949	0.0543	0.0510	0.54	0.94
NO_x	0.849	0.801	0.779	0.92	0.97
HC	0.0664	0.0319	0.0321	0.48	1.01
SO_2	0.136	0.127	0.127	0.93	1

marked. CO, HC and NO_x all contribute to photo-oxidant formation (LINDFORS et al., 1995).

The differences between the tractor emission values calculated for this study and the general values used in earlier work are large. Probable reasons for this are that the data used earlier are not from agricultural tractor measurements and the results are not weighted with factors adapted to agricultural conditions. In order to draw more definite conclusions about the large differences between the results , however, it is necessary to perform detailed emission measurements on more tractor engines.

Bilinear interpolation was used to derive the continuous function needed to calculate the emission values for all possible engine load-speed combinations. In order to study the effects of the choice of interpolation method, some of the calculations were also performed using a cubic spline method (DE BOOR, 1978) for the interpolation in the engine speed dimension, while the interpolation in the engine load dimension was not changed. The differences in the results were very small (0-2%) and no trends were found. Since the bilinear method is less complicated and very mathematically robust, it was therefore chosen for the calculations presented.

The LCI calculations show that the use of the new emission values result in major effects on the total emissions produced, especially for CO and HC, but also for NO_x and SO_2. The CO_2 production is decided by the fuel consumption and can therefore only be decreased by improved fuel efficiency. SO_2 production is decided by the sulphur content in the fuel and will be decreased by use of low-sulphur fuels.

The differences between emission results calculated from emission data for specific operations and using the average value calculated according to the ECE R49 standard, are very marked for single operations, but the differences decrease when all operations involved in wheat production are summed. The tendency, however, is that the ECE R49 value overestimates the CO and NO_x emissions, but underestimates the HC emissions. These tendencies were also found by Hedbom (1994). The large differences between emission values for specific operations and average values also indicate that comparisons of the environmental load of different crop growing systems have to be made using emission values for specific operations.

A general conclusion of the work is that LCA studies including agricultural crop production require high quality engine emission data, since these figures may have very important effects on the final results of the studies. In order to further improve the data quality, more studies on farm tractors and combine harvesters of different sizes and make are necessary.

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